Evolution of the 2007–2008 Arctic sea ice cover and prospects for a new record in 2008

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[1] The record Arctic sea ice minimum in 2007 has heightened debate on whether the Arctic Ocean has reached a tipping point, leading to a rapid transition towards a seasonal ice cover. Here, we review the 2007–2008 winter and spring ice and atmosphere conditions and assess how likely another record minimum is in summer 2008. At the end of June, 67% of the Arctic Ocean was covered by younger-than-average ice and only 5% was covered by older than-average-ice. Using a simple estimate based on ice survival rates, a new record low is reached in 2008 in 24 of 25 cases. With a more complex linear regression model, we suggest the September sea ice extent will be 4.40 million square kilometers, with a 40% chance that 2008 will set a new record low Arctic ice minimum. **Citation:** Drobot, S., J. Stroeve, J. Maslanik, W. Emery, C. Fowler, and J. Kay (2008), Evolution of the 2007–2008 Arctic sea ice cover and prospects for a new record in 2008, *Geophys. Res. Lett.*, *35*, L19501, doi:10.1029/2008GL035316.

1. Declining Sea Ice and the 2007 Record Minimum

[2] The decline in Arctic sea ice is one of the more compelling and obvious signs of climate change. Annual Arctic sea ice extent has decreased by about 4% per decade from 1979–2007, with a larger decline of roughly 10% per decade from 1979–2007 during September, the end of the summer melt season [*Stroeve et al.*, 2008; *Comiso et al.*, 2008]. The large decline in September sea ice is driven by several record or near-record minimums in the past few years, culminating in the exceptionally low 2007 sea ice minimum cover of 4.28 million km^2 (based on the mean monthly NSIDC sea ice index; http://nsidc.org/data/seaice_index/), which was 23% below the previous record set in 2005, and half as much as sea ice minimums from the 1950s through 1970s [e.g., *Stroeve et al.*, 2008].

[3] Last year's remarkable decline in sea ice was related to a number of factors, including a thinner spring ice cover that preconditioned the ice to extensive losses during summer [*Stroeve et al.*, 2008]; increased SSTs [*Steele et al.*, 2008] and increased basal melt from solar heating of the

upper ocean [*Perovich et al.*, 2008]; strong southerly winds along the dateline that promoted poleward heat transport and pushed ice into the central Arctic, and an enhanced ice-albedo feedback [*Zhang et al.*, 2008]. Enhanced solar input from abnormally clear skies may also have contributed [*Kay et al.*, 2008], although other studies discount this possibility [*Schweiger et al.*, 2008]. Following on from these reports, this paper addresses two key emerging questions from last year's record ice minimum:

[4] 1. Did the ice pack recover in winter and spring?

[5] 2. How likely is another record low sea ice extent in 2008?

2. Did the Ice Pack Recover in Winter and Spring?

[6] An examination of the winter and spring evolution of the Arctic ice cover and associated atmospheric conditions is important because numerous studies have shown that they play an important preconditioning role in defining the summer ice cover [e.g., *Rigor et al.*, 2002; *Drobot and Maslanik.*, 2003]. Following the record low last September, the ice re-grew at exceptional rates, and by mid-November 2007, the ice extent had reached the mid-November 2006 extent (Figure 1). By March, the 2008 ice cover was the largest winter maximum since 2003, ultimately coming to within 4% of the 1979–2000 mean maximum ice cover. Extending through April and May, the 2008 ice extent declined more rapidly than in 2007, and by the end of June, the 2008 ice extent approached the 2007 ice extent.

[7] Spatially, sea ice concentrations at the end of June, 2008, were much below normal in the eastern Beaufort Sea (Figure 2), associated with persistent easterlies that advected ice away from Banks Island. However, unlike 2007, southerly winds did not dominate in the western Beaufort/ Chukchi Sea region, and ice concentrations in 2008 remained near-normal in this region, whereas they were below normal in 2007 (Figure 2). Ice concentrations in the Kara and Barents Seas were also below normal in 2008, coinciding with above-normal air temperatures, but the ice concentration anomalies in this region were greater in 2007.

[8] Thus, although the June ice extents for 2007 and 2008 are similar, the spatial pattern of the where the ice cover has retreated this year differs from last year. However, the ice concentration analysis does not provide any information on ice thickness. This can be assessed somewhat following *Maslanik et al.* [2007], who compared ice age classes from *Fowler et al.* [2004] with ICESat-derived ice thickness estimates to develop an average ice thickness for each ice age class. As discussed by *Maslanik et al.* [2007], younger ice is thinner and thus, anomalous winter coverage of

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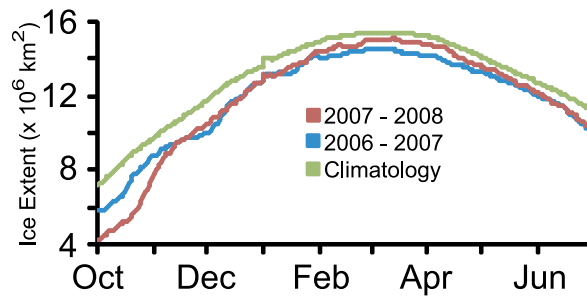
Figure 1. 2007–2008 Arctic sea ice extent from October through the end of June (red line) compared with the 2006–2007 record low (blue line) and 1979–2000 climatology (green line). Data based on NASA Team Algorithm, obtained from NSIDC.

younger ice increases the potential for rapid, extensive summer sea-ice loss.

[9] Through week 23 of 2008 (we use weekly time-steps for the ice age data because *Fowler et al.* [2004] compute ice age on a weekly time step; Jan 1 of a given year begins week 1, and 9 June 2008, represents the end of week 23 in 2008), first-year ice (FYI) dominated most of the Arctic Basin, including near the North Pole (Figure 3 (left)). Over all ocean areas from 70°N–90°N (an Arctic Ocean domain used by *Maslanik et al.* [2007]), younger-than-average ice covered 67% of the area and older-than-average ice covered only 5% of the area (Figure 3 (right)). The extent of multiyear ice (MYI) was also lower than at any point in the historical record, encompassing only 29% of the 2008 ice cover (Figure 4), whereas it covered roughly 50% to 60% of the ice cover in the early- and mid-1980s. The Arctic Ocean MYI extent in 2008 was also only 70% of the MYI extent at the end of week 23 in 2007, with the greatest difference seen in the coverage of ice between 2 and 4 years old. Moreover, the areal fraction of ice six or more years old in 2008 was only 6%, roughly 1/3 to 1/4 of the amount that existed in the 1980s.

[10] In summary, the 2008 sea ice extent somewhat recovered from the record low in 2007, but it remains thinner than at any time in the historical record, setting up the potential for another record low.

3. How Likely is Another Record in Summer 2008?

[11] At a very simplistic level, we can use the updated record of ice age data from *Fowler et al.* [2004] to compute survival rates for ice ages from past years, and then apply them to the current ice cover. In other words, we can determine what percentage of first-year ice survives to become second-year ice, what percentage of second-year ice survives to become third-year ice, etc. Based on survival rates from week 23 each year from 1983 to 2007, initialized with the 2008 ice-age distribution for the Arctic Ocean domain, a new record mean September ice extent minimum would have occurred in 24 of these 25 years (Figure 5). The lowest estimate is 2.30 million km^2, according to the survival rates from 2007, while the average of the 25 estimates is 3.62 million km^2, and the highest estimate is 4.49 million km^2, based on 1996 survival rates. Spatially,

the lack of older, thick MYI in the eastern Arctic (e.g., Figure 2), argues that the Northern Sea Route—the passage between Europe and Asia across the Siberian Arctic Ocean—may open this summer. It is also conceivable that ice-free conditions could develop at the North Pole, which our data show to be within or close to areas of predominantly first-year ice.

[12] The above method is obviously simplistic and it neglects a number of factors. For example, it is likely that survival rates for FYI in 2008 will be higher than they were in 2007, simply given the fact that FYI now covers so much more area than is typical and also at higher latitudes that receive less solar input during summer. A more sophisticated approach to forecasting is to use a statistical regression method as done by *Drobot* [2007] and *Lindsay et al.* [2008]. In this paper, we utilize four potential predictors to forecast the mean monthly annual sea ice minimum (again, based on the NSIDC Sea Ice Index): sea ice concentration, ice age, accumulated Freezing Degree Days (FDDs), and accumulated Thawing Degree Days (aTDDs). The main difference between this paper and *Drobot* [2007] is the replacement of the MYI index with an ice age-ice thickness (IAIT) index, which is based on the ice age-derived ice thickness from *Maslanik et al.* [2007]. From 1983 through 2007, the thickness for each age class is the same. However, for 2008, we reduced ice thickness in FYI by 0.2m, and ice thickness in other classes by 0.5m, based on preliminary analysis of ICESat freeboard estimates courtesy of R. Kwok that suggest that this spring's ice cover is thinner than it was in 2007 (see http://nsidc.org/arcticseaicenews). We recognize that ice thickness in the years preceding ICESat are not well-known, but even this rather crude ice age-ice thickness approximation provides a more realistic predictor of the sea ice minimum than the MYI index (r = 0.75 for the IAIT index and r = 0.56 for the MYI index). Additionally, the IAIT index is superior to MYI fraction because it provides information on multiple ice age classes beyond FYI vs. MYI, and also because it can be utilized in the summer (MYI estimates are not reliable once melt onset begins).
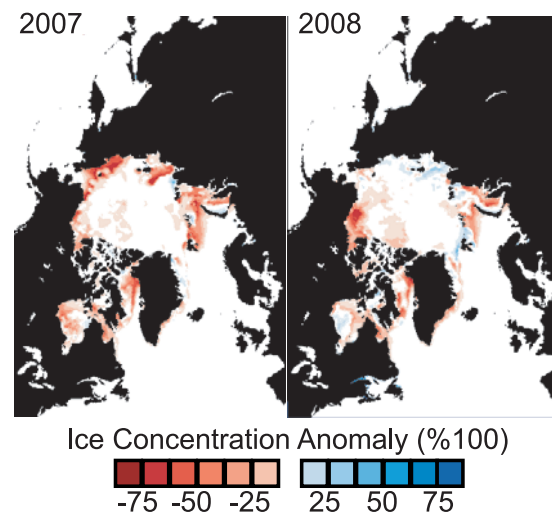

Figure 2. Sea-ice concentration anomalies with respect to 1979–2000 climatology for the end of June in (left) 2007 and (right) 2008. Data based on NASA Team Algorithm, obtained from NSIDC.
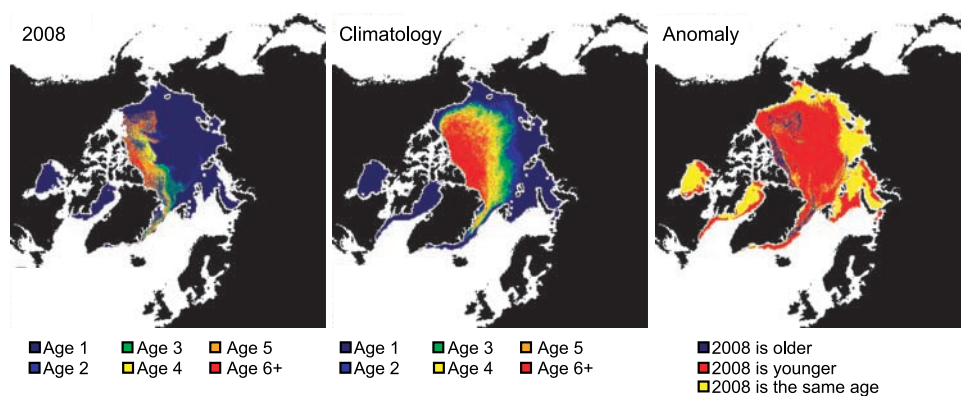
Figure 3. (left) Arctic sea ice age for week 23 (June 9), 2008; (middle) Climatological (1983–2000) Arctic sea ice age for week 23; and (right) 2008 Arctic sea ice age anomaly for week 23.
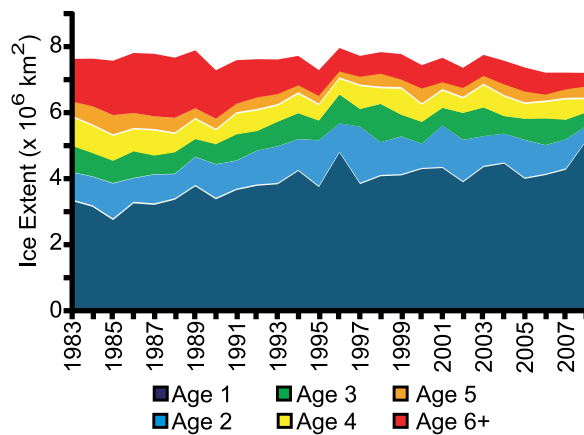
Figure 4. Fractional coverage of week 23 ice age classes for an Arctic Ocean domain (70°–90°N), 1983–2008.

Table 1. Final Regression Equation and Statistics

	Coefficient	Standardized Error	Standardized Coefficient	t	Sig.	VIF
IceExtent	0.482	0.083	0.572	5.671	<.0001	1.298
IAIT	0.366	0.081	0.515	5.112	<.0001	1.298

the number of pixels in that age class by the ice thickness for that class, which is derived by *Maslanik et al.* [2007]. Then, we simply sum the six values to obtain a weekly IAIT index score, which can be thought of as a proxy for mean ice thickness.

[15] The final forecast then follows from a simple step-wise regression, and the end result is a two-predictor equation, $y = 6.567 + 0.366*IAIT + 0.482*IceExtent$ (Table 1). Both the sea-ice extent and ice-age indices are retained, and because the standardized coefficient for ice extent is slightly higher (0.572 vs. 0.515), we suggest June ice extent plays a slightly larger role in influencing the minimum sea ice extent. The variance inflation factor (VIF) scores provide a quantitative assessment of the reliability of the coefficients, and with values of 1.30, multicollinearity is not adversely influencing the regression equation. Using a leave-one-out validation scheme, the regression equation has an r^2 of 0.77 and a mean absolute error of 0.30×10^6 km^2 (Figure 6). The largest error was for 1995 (0.82×10^6 km^2), and the smallest error was in 1986 (0.02×10^6 km^2). In 2007, the error was 0.40×10^6 km^2, suggesting that the equation is fairly robust even for extreme cases.

[16] For 2008, the most likely solution is 4.40×10^6 km^2, and there is a 40% probability of setting a new record below the 4.28×10^6 km^2 from 2007. These results qualitatively concur with numerical simulations by *Zhang et al.* [2008], who suggested that another extreme reduction in ice cover as seen in 2007 is unlikely unless atmospheric circulation patterns occur that are significantly different than in the past. In their results, atmospheric forcings similar to those in 2007 would yield a reduction in ice extent similar to that seen in 2007, as we predict here.

[17] In summary, our regression analysis suggests that the 2008 sea ice minimum will approach the level seen in 2007. We note however that this ignores the evolving summer conditions, which will have a large impact on the resulting

[13] Given that the ice age data are compiled at weekly intervals, all potential predictors are developed with data available through week 23 of a given year. The sea-ice concentration is based on a 5-day minimum filter of NASA Team Algorithm sea-ice concentrations. Freezing Degree Days (FDDs) and Thawing Degree Days (TDDs) are based on the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] and they are accumulated daily from October 1 of the previous year and January 1 of the concurrent year, respectively. We use reanalysis data here instead of APPx data [i.e., *Drobot*, 2007], because the APPx data are not archived post-2004.

[14] *Drobot* [2007] provides complete details on the specific regression method, but briefly, sea ice concentration, FDD, and TDD index values are computed via a "correlation-weighted time series", which is created by initially correlating the predictor data at each pixel with the annual sea ice minimum. This provides a spatial map of correlation coefficients that signifies the strength of relationship between variations in the sea ice concentration, FDDs, and TDDs with the annual sea-ice minimum (see *Drobot* [2007] for examples of these types of spatial maps). For the IAIT index, we do not use the "correlation-weighted time series" directly because there are only six discrete ice age classes. Instead, for each age class, we initially multiply
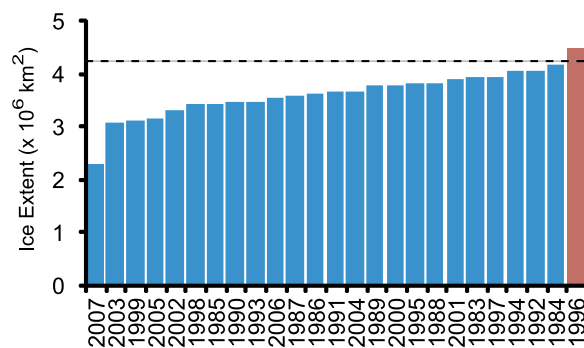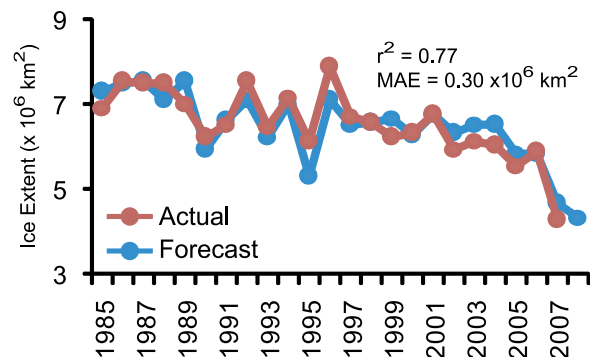

Figure 5. Estimated 2008 minimum sea ice extent based on survival rates computed for week 23. The dashed line is the 2007 minimum sea ice extent (4.28×10^6 km^2), and only one year (1996) fails to produce a new record in 2008.

Figure 6. Estimated minimum sea ice extent from 1985 through 2008, based on the *Drobot* [2007] approach. The 2008 forecast is 4.40×10^6 km^2.

ice extent in September. In addition, the fracturing of the MYI in the Beaufort Sea together with a current dipole pressure pattern (high over Greenland and Canada, low over Siberian Oceans) suggests large ice losses in this region are possible. We will continue to monitor conditions throughout the summer, and updates to the prediction will be given at http://ccar.colorado.edu/~arifs.

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